Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **475,** 353–358 (2018)
Advance Access publication 2017 December 12
doi:10.1093/mnras/stx3193

Spectroscopy of five V-type asteroids in the middle and outer main belt

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Accepted 2017 December 7. Received 2017 December 7; in original form 2017 June 28

ABSTRACT

The origin of basaltic asteroids found in the middle and outer main belt is an open question. These asteroids are not dynamically linked to the Vesta collisional family and can be the remnants of other large differentiated asteroids present in the early phases of the main belt but destroyed long ago. Spectroscopic investigation of some V-type asteroids in the middle-outer belt, classified as such by their SLOAN photometric colours (Ivezić et al.) and WISE albedos (Masiero et al.), has revealed that their spectra are more similar to other taxonomic classes, like –Q, R, S, or A (Jasmim et al. and Oszkiewicz et al.). Here, we report about the observation, in the near-infrared spectral range, of five V-type asteroids located beyond 2.5 au. These observations allowed us to infer their taxonomic classification. Two asteroids, (21238) Panarea (observed in a previous campaign but here included for comparison) and (105041) 2000 KO41, confirm their basaltic nature. For asteroids (10800) 1992 OM8 and (15898) Kharasterteam a taxonomic classification is more uncertain, being either Q- or S-type. Asteroid (14390) 1990 QP10 classification is difficult to ascribe to the known taxonomic classes, maybe due to the low-quality spectrum. Further observations are desirable for this asteroid.

Key words: techniques: spectroscopic telescopes – minor planets, asteroids: individual: Vesta.

1 INTRODUCTION

The majority of V-type asteroids are found in the inner main belt, in the region between 2.1–2.5 au, although a few have also been observed in the near-Earth region (McFadden et al. 1985; Cruikshank et al. 1991; Binzel et al. 2004; Duffard et al. 2006; Reddy, Nathues & Gaffey 2011; Reddy et al. 2015) and in the middle-outer main belt (Lazzaro et al. 2000; Binzel, Masi & Foglia 2006; Roig et al. 2008). These asteroids have surface compositions that resemble that of the 530 km sized asteroid (4) Vesta. Their spectra present strong absorption features, centred near 0.9 and 1.9 µm, which are indicative of basaltic material, being due to the presence of Fe^{2+} in pyroxenes. These minerals are formed when the silicates melt, implying an extensive geochemical differentiation and resurfacing. However, according to our current understanding and modelling, it is believed that such differentiation should not occur on small-size objects (Ruzicka, Snyder & Taylor 1997), but only on large and early formed planetesimals in the inner Solar system. Thus, most of the small basaltic asteroids should be fragments of larger differentiated bodies, such as the Vestoids, which are members of the dynamical family of (4) Vesta (De Sanctis et al. 2012; Marchi et al. 2012; McSween et al. 2013).

With the unique exception of (4) Vesta, there are no other nearly intact large differentiated asteroids in the main belt. Thus, to explain the origin of the basaltic asteroids not dynamically linked to (4) Vesta there are two possibilities: (i) all basaltic material do indeed originate from Vesta, and the problem lies in our inability to trace the dynamical path they should have followed, or else, (ii) they derive from basaltic progenitors completely destroyed long ago and no more recognizable, not even as a dynamical family. Spectral studies on the HEDs (Howardite–Eucrite–Diogenite) meteorites allowed pointing out differences on the analysed samples, which are compatible with the presence of multiple large basaltic asteroids, at least in the early phases of our Solar system. The basaltic nature of these meteorites indicates that there were diverse differentiated asteroids and basaltic material in the inner Solar system (McSween et al. 2011; Benedix et al. 2017).

Few V-type asteroids, located at heliocentric distances greater than 2.5 au, have been spectroscopically investigated in order to derive their basaltic nature, in particular, (1459) Magnya (Lazzaro et al. 2000; Hardersen, Gaffey & Abell 2004), (21238) Panarea (Hammergren, Gyuk & Puckett 2007; Binzel et al. 2006; De Sanctis et al. 2011a), (40521) 1999 RL95 (Roig et al. 2008), (7472) Kumakiri, and (10537) 1991 RY16 (Duffard & Roig 2009). All of these V-type asteroids seem to have no connection with (4) Vesta either due to their dynamical characteristics or to their spectra and derived mineralogies (Hardersen et al. 2004; Moskovitz et al. 2008;

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Table 1. Observing conditions for the analysed asteroids. The proper orbital parameters are taken from the astdys web site (http://Hamilton.dm.unipi.it/astdys2/catalogs/allnum.pro), while the diameters are from Mainzer et al. (2016). Marked by an asterisk are diameters computed assuming an albedo of 0.361 for Vesta, obtained as the average of the WISE albedo for the V-types belonging to the Vesta family (Masiero et al. 2013).

Asteroid	Date	e	H	Diameter (km)	Airmass	Phase (°)	Solar analog star
(10800) 1992 OM8	23-Nov-2009	0.0924	14.2	3.29	1.09	12.8	Land 115–27
(14390) 1990 QP10	21-Mar-2010	0.1032	12.1	10.77	1.37	16.3	Land 98–978, Land 107–998
(15898) Kharasterteam	15-Mar-2012	0.0932	13.0	5.63*	1.07	11.2	Land 98–978, Land 107–998
(21238) Panarea	25-Dec-2007	0.1372	13.1	5.22	1.41	16.9	Land 102–1036, Land 115–27
(105041) 2000 KO41	22-Mar-2010	0.1593	14.5	2.82*	1.25	4.5	Land 98–978, Land 107–998

Duffard & Roig 2009; De Sanctis et al. 2011a). In addition, the AVAST (Adler V-Type Asteroid) survey, using the spectral range from 0.36–1.0 µm, has classified six V-type asteroids with orbital semi major axes greater than 2.5 au (Solontoi et al. 2012). The presence of all of these putative basaltic asteroids, at large heliocentric distances, is difficult to explain with the present dynamical and thermo-physical models.

In this context, therefore, it is important to increase the sample of spectroscopically studied V-type asteroids beyond 2.5 au in order to assess their relationship to (4) Vesta and its family members, the Vestoids. In particular, the detailed study of these objects can give us insight on differentiated asteroids that might have existed in the main belt. Moreover, the study of their mineralogy can help in understanding the differentiation process of small planetary bodies at larger distance from the Sun. Most of the models of differentiation process indicate that this process was likely driven by radiogenic decay of short-lived isotopes, such as ^{26}Al and ^{60}Fe (Grimm & McSween 1993; Goswami & Vanhala 2000). However, the short decay times of these radionuclides pose strong limitations on the time and location of the differentiated planetesimals. These small bodies, which underwent differentiation, must have accreted and differentiated very early in the inner Solar system, when the short lived radio-isotopes were abundant and sufficient to melt the silicate. Conversely, small basaltic bodies in the middle-outer belt are difficult to explain within the current formation theories, which indicate that differentiation of small planetesimals could not have occurred at large distance from the Sun. It is especially interesting to note one apparently igneous asteroid, (221) Eos and its associated family, in the outer main belt, which may represent a partially differentiated chondritic body (Mothé-Diniz et al. 2008).

Aiming to establish if other basaltic asteroids might be found in the middle and outer belt, several methods have been developed and applied to photometric surveys, in particular, the SDSS-Moving Object Catalog – MOC (Ivezić et al. 2001) to select candidate, or putative, V-type asteroids (Roig and Gil-Hutton 2006; Moskovitz et al. 2008; Carvano et al. 2010; Oszkiewicz et al. 2014). More recently, Licandro et al. (2017) used colours from the VISTA–VHS survey and identified about 19 asteroids compatible to V-types. We have yet independently selected and confirmed the basaltic nature for the middle main belt asteroid (21238) Panarea (De Sanctis et al. 2011a), through observations in the near-infrared (NIR) spectral range.

Here, we will describe new NIR spectroscopic observations of five of these candidates, located in the middle-outer belt, i.e. with $a > 2.5$ au. They were observed in the framework of an observing proposal at Telescopio Nazionale Galileo (TNG), during several periods from 2007 December to 2012 March. The observed asteroids show strong 0.9 and 1.9 µm absorption features indicative of differentiated objects. Moreover, certain peculiarities in their spectra deserve special attention in future studies. The results are discussed in the context of the basaltic material in the asteroid belt.

This paper is organized as follows: observation circumstances are presented in Section 2; the obtained spectra are presented in Section 3 and discussed in Section 4. Conclusions follow.

2 OBSERVATIONS AND DATA REDUCTION

We present the spectroscopic investigation of a sample of V-type asteroids located in the middle and outer main belt. Four among these are new ones, and one, (21238) Panarea, although previously published by our team (De Sanctis et al. 2011a) is reported again here for comparison reasons. Two more asteroids, (7472) Kumakiri and (127242) 2002 JG28, were observed in bad weather conditions resulting in a quite noisy spectrum and, thus, neither presented nor discussed here. It must be pointed out, however, that asteroid (7472) Kumakiri has been previously observed by several authors (Duffard & Roig 2009; Burbine et al. 2011; Solontoi et al. 2012; Hicks et al. 2014) revealing its very special spectrum, which is more compatible to that of O-type asteroids.

NIRspectra of the asteroids have been acquired with the TNG, in La Palma, from 2009 November to 2012 March, in three different observing runs, while (21238) Panarea was observed in 2007 December. We used the Near-Infrared Camera Spectrometer (NICS) equipped with the Amici grism, and a 2-arcsec slit. The selected setup, which allows one to cover the 0.8–2.5 µm spectral range, is useful to investigate the spectral properties of faint and small objects. The observations were completed with solar analog stars (Land 98–978, Land 102–1036, Land 110–361, Land 107–998, Land 115–27), to correct the telluric and solar influences. Data reduction includes flat fielding and sky correction, and is carried out with standard techniques, described in De Sanctis et al. (2011a,b). The spectra are, thus, normalized to 1 at 1.6 µm for comparison with our previous observations (Duffard et al. 2004; De Sanctis et al. 2011a,b; Migliorini et al. 2017). Table 1 summarizes the observing circumstances and asteroid physical parameters. The diameter given is from the WISE survey (Mainzer et al. 2016) or, when not available (indicated by an asterisk), is computed using an albedo of 0.361, which is the mean albedo of the Vesta family according to Masiero et al. (2013).

The observed asteroids are located outside the Vesta region, as shown in Fig. 1, where the position of objects discussed in this paper is identified with a star. In particular, asteroids (10800) 1992 OM8, (15898) Kharasterteam, and (21238) Panarea are located in the middle main belt ($2.5 < a < 2.8$ au), while the other two in the outer belt ($2.8 < a < 3.2$ au).

The reflectance smoothed spectra of the observed asteroids are given in Fig. 2. Despite the low signal-to-noise ratio of some spectra, which is mainly attributable to the weather conditions along with the faintness of the objects, it is possible to recognize the deep absorption at about 0.9–0.94 µm, in most of them. This band is typical of basaltic material. On the other hand, the band at 2 µm is clearly detected only in the case of asteroids (21238) Panarea and

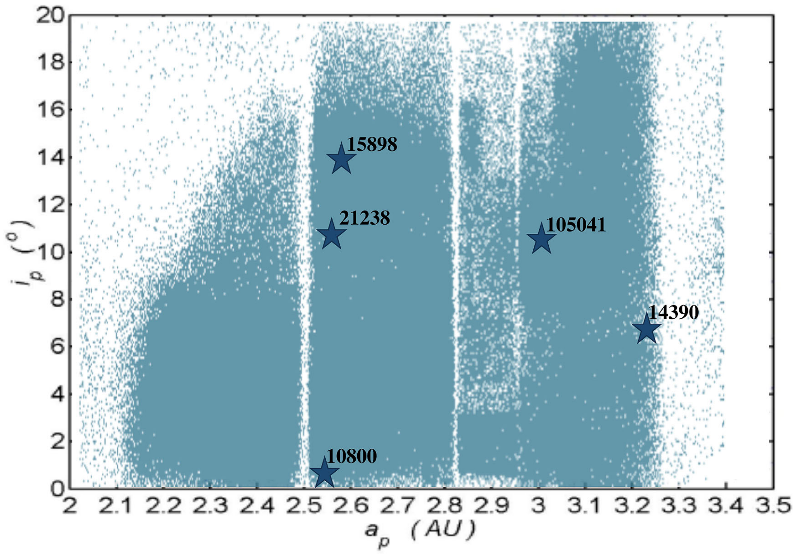

Figure 1. Position of the asteroids discussed in this paper, in the main belt region, identified with a star. The Vesta family region is located in the inner belt, with $a_p < 2.5$ au, while the studied asteroids are in the intermediate and outer region, beyond the 3:1 resonance, located at about 2.5 au.

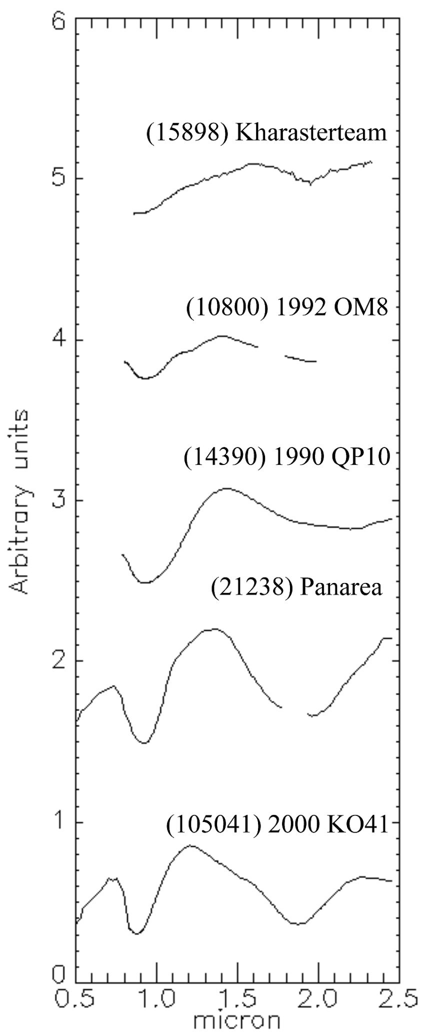

Figure 2. Smoothed spectra of asteroids discussed in this paper. The spectral region at about 1.8 µm is masked for asteroids (10800) 1992 OM8 and (21238) Panarea because of atmospheric features not properly corrected.

(105041) 2000 KO41. In the case of asteroid (14390) 1990 QP10 this band seems to be present, although not so strong as in the previous objects. This is not the case for asteroids (15898) Kharasterteam and (10800) 1992 OM8 where their spectra do not present the 2 µm band, or if present, it is very swallow in comparison to the typical V-types. Moreover, the spectra of these two asteroids show a different slope in the 1-1.5 µm region, which might be indicative of a different taxonomic classification. Note also that the poor signal-to-noise ratio in the spectra of these asteroids might be the cause for not being able to identify the band.

Characteristics of each of the observed asteroids will be discussed in the following sections.

3 RESULTS

Due to the quality of some of the observed spectra, the mineralogical analysis based on the Band I (at 0.9 µm) and Band II (at 2 µm) centres and their separation, already applied to data acquired during previous observing campaigns (Duffard et al. 2004; De Sanctis et al. 2011a,b; Migliorini et al. 2017), cannot be used here. Hence, the acquired spectra will be used to taxonomically classify the observed asteroids performing comparisons with the mean spectra of O-, Q-, R-, S-, and V-types as defined by Demeo et al. (2009).

According to Demeo et al. (2009), V-type asteroids are characterized by a strong narrow absorption band at 1 µm, and a second strong wider band at 2 µm. Classes R, Q, and O are quite similar to the V one, but differences in the band centres and shapes are present. The R-types present a 1-μm feature broader than the V-type and a shape more similar to an S-type asteroid, although deeper than in the latter case. The spectra of O-type asteroids have a very rounded and deep bowl-shaped feature at 1µm and a strong one at 2 µm. The Q-class is characterized by a deep and distinct 1 µm absorption feature, another feature near 1.3 µm and a 2 µm band with varying depth among objects. In the following, spectral properties of asteroids reported in Fig. 2 are discussed.

3.1 Asteroid (15898) Kharasterteam

Asteroid (15898) Kharasterteam has not the well-defined band at 0.9 µm, which makes its identification as a V-type very difficult.

According to the taxonomy by Demeo et al. (2009), it seems to be better classified as a S-type or a Q-type. The band at 2 µm, is not well defined, due to atmospheric contamination, and, if present, is very shallow. Hence, we cannot unambiguously classify the asteroid.

3.2 Asteroid (10800) 1992 OM8

The spectrum of asteroid (10800) 1992 OM8 shows a band at about 1 µm, while it is difficult to clearly identify the one at 2µm. Despite the low signal to noise ratio, it is clear that the spectral slope at 1-1.5µm is less steep than in the case of typical V-types, while the possible absorption band beyond 1.5µm is less deep than the pyroxene one observed in the V-type asteroids. The comparison of the smoothed spectrum of this asteroid with other classes templates from Demeo et al. (2009) seems to indicate that it can be classified as S-type or Q-type.

3.3 Asteroid (14390) 1990 QP10

The spectrum of asteroid (14390) 1990 QP10 is quite difficult to assign to a known class. Relative to V-type asteroids, the 1 µm band is broader and the 2 µm band is shallower, although the latter might be affected by atmospheric contribution, not well removed. Comparing our spectrum with the template of O-type asteroids, it is possible to see similarities in the 2 µm band, but the 1 µm band is much broader. Moreover, it appears that band I minimum does not match. We thus conclude that it may be a unique example of new taxonomic class. Further investigation is required for this very unusual asteroid.

3.4 Asteroid (21238) Panarea

Asteroid (21238) Panarea was observed in 2007 and its spectral properties are discussed in a previous paper by De Sanctis et al. (2011a). Including the visible part by Solontoi et al. (2012), it clearly classifies as a V-type in the Demeo et al. online tool, although presenting differences in the band properties. In particular, it shows a very strong and narrow absorption centred at 0.915 ± 0.002 µm, and a strong absorption centred at 1.907 ± 0.005 µm, as derived in De Sanctis et al. (2011a). In addition, its spectral slope is quite steep. The mineralogy inferred from band analysis shows a calcium content [Wo] ranging between 1.6 and 3.4 mol, and a iron content [Fs] in the range 21.7 and 27.6 mol, according to formulae from Gaffey et al. (2002) and Burbine, Buchanan & Binzel (2007). Formal errors are of the order of ±4–5 per cent of the derived molar concentration according to Gaffey et al. (2002) and of ±1–4 per cent following the Burbine's formulation. In the case of asteroid (21238) Panarea, the derived values are within the associated errors, and are compatible with a completely diogenitic composition (De Sanctis et al. 2011a).

3.5 Asteroid (105041) 2000 KO41

The spectrum of asteroid (105041) 2000 KO41 presents two wide absorption bands, located at 0.922 ± 0.01 µm and at 1.851 ± 0.012 µm. In comparison with the template of V-type asteroids (from Demeo et al. online tool), the two bands are slightly shifted towards shorter wavelengths. Moreover, the slope between 1–1.3 µm is steeper. Comparison with other templates shows no similarity with any other class. The shape of the spectrum is very similar to that of asteroid (21238) Panarea discussed above, but with band centres at shorter wavelengths.

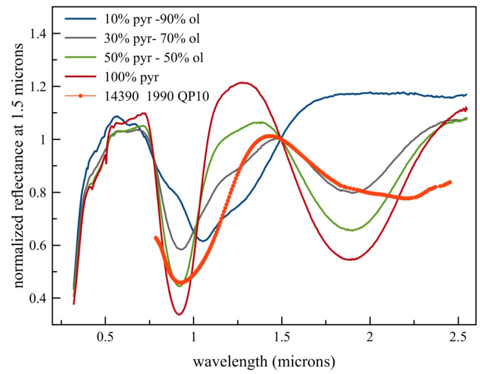

Figure 3. Comparison between the spectra of asteroid (14390) 1990 QP10 and synthetic spectra obtained by mixing olivine and orthopyroxenes in different proportions.

4 DISCUSSION

Among the observed asteroids, only (21238) Panarea and (105041) 2000 KO41 present spectra compatible with basaltic material, while different classification is suggested for the rest of the sample. It is important to recall that (21238) Panarea has been already analysed in De Sanctis et al. (2011a) and is used here just for comparison. Although the observed sample has been selected on the basis of the visible colours of the asteroids, which are compatible with the V-type taxonomic class, their NIR counterpart does not confirm this classification. Two asteroids, (10800) and (14390), present spectra more compatible to ordinary chondrite, or Q-type, while (15898) Kharasterteam to S-type, characterized by shallow bands at 1 and 2 µm.

The spectrum of asteroid (10800) 1992 OM8 shows a broad-band at 1 µm and a very shallow 2 µm feature, being compatible with that of Q-type asteroids. In the case of asteroid (14390) 1990 QP10, the spectrum has a large, strong and complex 1 µm band and a large and shallow band at 2 µm. The band at 1 µm is very unusual, blow-shaped and possibly due to the overlap of different absorptions. Although we cannot completely exclude that the strange shape is due to a low-quality spectrum, the comparison of this asteroid with mixtures of olivine and orthopyroxenes in different proportions (Fig. 3) shows that the maximum at about 1.45 µm in the spectrum of (14390) 1990 QP10 might indicate the presence of olivine mixed with pyroxene, while the second band is not compatible with any olivine-pyroxene mixture. Laboratory olivine spectra exhibit only a broad, asymmetric 1 µm feature due to the overlapping of three individual absorptions, whereas orthopyroxene exhibits two well-defined, symmetric absorptions near 1 and 2 µm. Spectra of mixtures of olivine-orthopyroxene show that large olivine contents (higher than 50 per cent) produce distortion of the band shape near 1 µm from that of pure pyroxene (orange line). A sensitive indicator of the presence of olivine in a mixture is a shallow depression near 1.3 µm that produces a shift of the maximum at about 1.5 µm and a reduction in depth of BII pyroxene absorption.

The only two asteroids classified as basaltic, (21238) Panarea and (105041) 2000 KO41, are however, quite distinct from the typical V-type asteroids. They both show very prominent pyroxenes bands shifted towards shorter wavelengths with respect to the typical V-types. The position of band centres can vary with the different amount of Ca and Fe (Adams 1974; Hazen et al. 1978; Cloutis & Gaffey 1991); thus, by knowing the band centres, we are able to identify the type of pyroxenes present on the asteroids surface (Burbine et al. 2007). Both the 1 and 2 µm bands of pyroxenes move

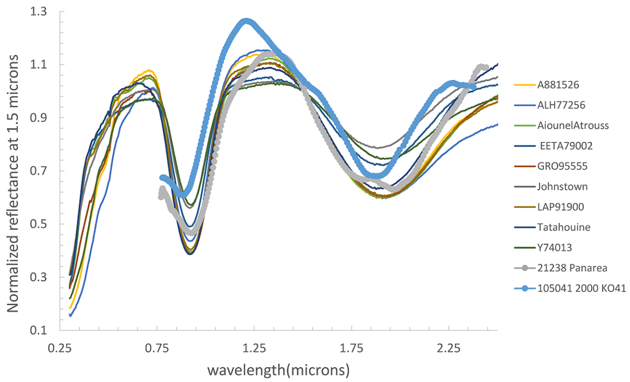

Figure 4. Spectra of asteroids (21238) Panarea and (105041) 2000 KO41 compared with those of different diogenites.

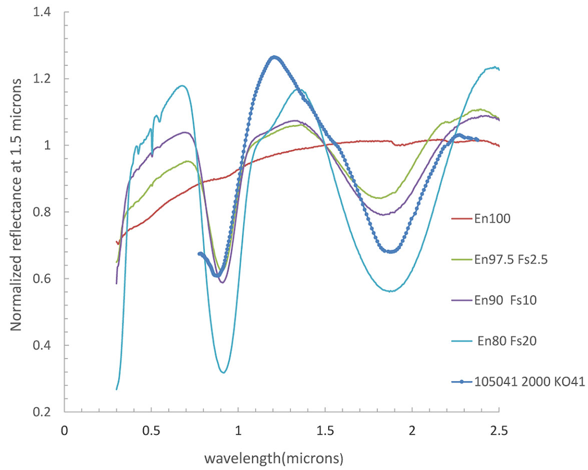

Figure 5. Spectrum of asteroid (105041) 2000 KO41 in comparison with that of synthetic pyroxenes with different proportions of Mg and Fe (from Klima et al., 2007).

regularly to longer wavelengths with increasing Fe and/or increasing Ca content. This trend is also found in the band centre of the eucrite, diogenite, and howardite meteorites, basaltic meteorites that are originated from (4) Vesta (McSween et al. 2013; De Sanctis et al. 2012, 2013). Petrographic models assume that eucrites are formed from residual basaltic liquids that extruded on to the surface of the parent body, whereas diogenites are cumulate rocks directly crystallized from a magma ocean (e.g. Righter & Drake 1997; Takeda 1997; Warren 1997). Howardites are breccias derived by the mixture of the eucrites and diogenites. The HED meteorites spectra show well-defined absorption bands at around 0.95 μm (Band I) and 1.9 μm (Band II), and diogenites and eucrites show quite distinct band centre. Typically, diogenties have Band I centres in the range 0.92–0.93 μm and Band II centre between 1.88–1.94 μm (Beck & McSween 2010; Klima et al. 2007; De Sanctis et al. 2011a).

A comparison between diogenites and asteroids (21238) Panarea and (105041) 2000 KO41 is provided in Fig. 4. It shows that the two bands are clearly present in the spectra of the two asteroids, but they are shifted towards shorted wavelengths, this trend being more evident in asteroid (105041) 2000 KO41. We further compared the spectrum of this asteroid with that of different synthetic pyroxenes from Klima et al. (2007) (Fig. 5). Synthetic pyroxenes with different Fe and Mg content show distinct spectra, with strong differences in band centre with the increase of Fe (Fs) or Mg (En) content (Fig. 5). It can be noted that Band I and Band II of asteroid (105041) 2000 KO41 are mostly compatible with pyroxenes very poor in iron. In particular, the Band I minimum is at very short wavelength.

Noteworthy is the fact that the non-confirmation of the basaltic nature of asteroids classified as V-type by their visible colours is in agreement with results from other authors. In particular, this being true for V-type asteroids located in the intermediate and outer main belt, outside the Vesta region. For example, Jasmim et al. (2013) analysed VNIR spectra of asteroid (7302) 1993 CQ, located at 2.81 au in the outer region of the belt and classified as V_p by Carvano et al. (2010), and derived spectral parameters for this asteroid, which are compatible with ordinary chondrites, and a spectrum similar to Q-type asteroids. This seems to be the case of two asteroids of our sample, (10800) and (14390), located in the intermediate and outer belt, respectively. More recently, Oszkiewicz et al. (2014) derived a new methodology to select putative V–type asteroids from SLOAN colours (Ivezić et al. 2001) and WISE albedos (Masiero et al. 2011). The observation of six of these putative V-type asteroids, however, revealed that only one confirmed to be V-type, the rest being better classified as A-, Q-, or S-type.

5 CONCLUSIONS

The spectra of five possible V-type asteroids, located in the middle-outer belt, are presented here. For two of them, (21238) Panarea and (105041) 2000 KO4, we confirm their basaltic nature, although the positions of band I and II are slightly shifted towards shorted wavelengths with respect to the typical V-type belonging to the Vesta family. Asteroid (105041) 2000 KO41 is located quite far from the Vesta region, and this poses the question about its link to other basaltic parent bodies. Moreover, based on their unusual mineralogy, we suggest that these two asteroids are not scattered from the (4) Vesta, but fragments of different differentiated parent bodies.

We show here that the spectrum of asteroid (14390) 1990 QP10 is peculiar, due to the large rounded shaped 1 μm band, and clearly different from any known spectral classes, requiring further investigations to understand its mineralogy.

The remaining two asteroids of our sample, (10800) 1992 OM8 and (15898) Kharasterteam, can be classified as Q- or S-types.

The results here presented clearly stress that only NIR observation can confirm the nature of V-types identified as such by visible colours or spectra. Moreover, it points out the need to increase the sample of confirmed basaltic asteroids in the middle and outer main belt. It is noteworthy up to the present and to our knowledge that only one asteroid in the middle belt, (21238) Panarea (Moskovitz et al. 2010; De Sanctis et al. 2011a) and two in the outer, (1459) Magnya (Lazzaro et al. 2000; Hardersen et al. 2004) and (105041) 2000 KO41 (this paper) do have published V and NIR spectra. Another middle-belt V-type asteroid, (40521) 1999 RL95, has been characterized only in the V spectral region (Roig et al. 2008; Oszkiewicz et al. 2014). On the other hand, in the inner main belt there are about 130 asteroids not members of the Vesta dynamical family (Vestoids) spectroscopically characterized as basaltic, 71 of which in the NIR spectral range and 60 in the visible, while in the near-Earth region other 37 asteroids, 28 in the NIR and 9 in the visible range. Only with a larger sample it will be possible to set constrains on the existence and kind of other large differentiated body(ies) present and collisionally disrupted in the early phases of the Solar system in the asteroid belt.

ACKNOWLEDGEMENTS

The authors thank the reviewer for the fruitful discussion that helped improving this paper.

DL was supported by diverse grants and fellowship by Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

This work is based on observations made with the Italian TNG operated on the island of La Palma by the Fondazione Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Taxonomic type results presented in this work were determined, in whole or in part, using a Bus-DeMeo Taxonomy Classification Web tool by Stephen M. Slivan, developed at MIT with the support of National Science Foundation Grant 0506716 and NASA Grant NAG5-12355.

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